Int J Life Cycle Assess (2010) 15:896–906
DOI 10.1007/s11367-010-0222-1

LCA OF WASTE MANAGEMENT SYSTEMS

A comparison among different automotive shredder residue treatment processes

Luca Ciacci · Luciano Morselli · Fabrizio Passarini · Alessandro Santini · Ivano Vassura

Received: 23 February 2010 / Accepted: 5 July 2010 / Published online: 18 July 2010

Abstract
Background and purpose European Community claims for end-of-vehicles (ELVs) targets of at least 85% recycling and 95% recovery rate by 2015. At present, only about 80% of ELV total weight is being recycled, whereas the remaining fraction of 20%, which is called automotive shredder residue (ASR), is disposed by landfilling in most of the EU countries. In this study a comparison has been carried out among five ASR management strategies, chosen after a screening of the most common technologies suitable and available nowadays, aiming at proposing alternatives to the current disposal in terms of benefits resulting from the conservation of nonrenewable resources and reduction of wastes disposal. These scenarios are ASR landfill disposal, the current status quo for a further nonferrous metals recovery, ASR incineration with energy recovery, an advanced material recovery followed by thermal treatment of ASR residue and a feedstock recycling by means of gasification.
Methods Life Cycle Assessment (LCA) methodology was applied in order to characterise and quantify the environmental impacts related to each scenario analysed, using the SimaPro 7.1 software and the Eco-indicator'99 method, according to a hierarchic approach.
Results and discussion The analysis shows that recovering nonferrous metals ensures a reduction of the environmental loads related to resources depletion due to landfill disposal, but no significant benefit for human health end point can be observed. The ASR thermal treatment in incinerators allows both the decrease of impacts due to plastic fraction disposal and benefits from energy recovery, but a decrease of ecosystem quality occurs because of stack emissions. A net environmental performance upgrading seems to be ensured by those scenarios which include the application of post-shredder technologies.
Conclusions Industrial processes aimed to matter recovery, after shredding, resulted not only in a necessary solution to fit the European recovery and recycling targets for ELVs but also to the options that can obtain greater environmental benefits compared to present practises. However, further improvement can be achieved only by integrating end-of-life treatments into Eco-design strategies aiming at a more efficient separation of high value-added materials such as plastics and metals.

Keywords Automotive shredder residue (ASR) · Car fluff · Ecoindicator · Environmental assessment · Material recovery · Post-shredder technologies

1 Introduction

1.1 Background, aim and scope

About 10 million tonnes of waste are generated in Europe from end-of-vehicles (ELVs) management chain every year (ACEA 2009). Currently, 80% of the ELV total weight is recycled (Nourreddine 2007; Funazaki et al. 2003; Ferrão et al. 2006) during the end-of-life treatment phases; namely, (i) pretreatment, which is mandatory, and it is aimed at removing most of hazardous components such as batteries, fuels and lubricating oils; (ii) dismantling, which consists of components removal from the car body in order to reuse them, if undamaged, or recycle material, e.g. as it happens for glass from windscreens and plastics bumpers in

L. Ciacci · L. Morselli · F. Passarini (✉) · A. Santini · I. Vassura
Department of Industrial Chemistry and Materials, Alma Mater Studiorum, University of Bologna,
viale Risorgimento 4,
40136 Bologna, Italy
e-mail: fabrizio.passarini@unibo.it

the Netherlands (GHK/Bios 2006; Dalmijn and De Jong 2007); finally, (iii) shredding phase, in which ELVs are turned into pieces in order to release ferromagnetic scraps allowing separation and recovery. This metallic fraction amounts to around 60% of the total weight (Ferrão et al. 2006).

The remaining 20% is called automotive shredder residue (ASR) and, at present, it is disposed by landfilling in most European countries (Eurostat 2009) considered either a hazardous waste or a municipal solid waste depending on the results of chemical characterisation. The complexity of ASR composition, due both spatial and temporal variations, as well as the different source materials shredded (i.e. vehicles and white goods) puts several limits over material recycling processes. Table 1 shows the average ASR composition reported from literature (Nourreddine 2007; Boughton and Horvath 2006; De Filippi et al. 2003) confronted with the one used for this study. The data set used in this study comes from a dedicated trial which involved the main Italian players in ELVs industrial chain (Morselli et al. 2010; AIRA 2007).

The quantity of ASR is likely to grow in the forthcoming years due to the increasing amount of polymers replacing metals in new vehicles. ASR valorisation treatments are necessary according to the limit of 13 MJ/kg stated for waste disposal by the European Directive 1999/31/EC, enforced with D.Lgs. 36/2003 by the Italian Parliament. Furthermore, the Directive 2000/53/EC claims for ELVs at least 85% recycling rate and 95% recovery rate by the year 2015, thus allowing the disposal in landfill for maximum 5% ELV total weight. The reduction of the current percentage by recovering materials and energy is thus a major challenge for European Community.

In this study a comparison among five ASR management strategies is carried out with a characterisation and a quantification of environmental impacts related to each scenario investigated by means of a Life Cycle Assessment (LCA) approach. Scenarios were chosen after a screening involving the most common and used technologies, aiming at proposing alternatives to the current disposal in terms of benefits resulting from the conservation of nonrenewable resources and reduction of waste disposal.

SimaPro software 7.1 and ecoindicator'99 method with hierarchic approach were used to carry out the LCA analysis for this study.

1.2 ASR management strategies investigated

The treatment of ASR involves the separation of high value-added materials such as polymers and nonferrous metals in addition to ferromagnetic fraction. Ferrous metal separation and recycling is a well-established procedure performed by shredding operators with nearly 100% efficiency depending on the type of shredder and working conditions, i.e. about 60% of ELV total weight (Ferrão et al. 2006; Nourreddine 2007).

Most of all current separation technologies carry out a material recovery from waste by means of methods based on physical, magnetic, chemical or electrical properties of materials. Nevertheless, while metal recovering processes are now steady and economically sustainable, plastic matters generate often overlapping in properties due to the presence of fillers, modifiers, additives and plasticizers added to polymers during production phases. From this, separation processes for plastics present more difficulties to deal with and put limits on the purity rates that can be achieved (Gent et al. 2009; Ferrão and Amaral 2006; La Mantia 2002; Reuter et al. 2006; Scheirs 2001).

However, it appears that both for material recycling and energy recovery an ASR treatment is necessary in order to remove noncombustible fraction such as inert materials, fines, dusts, pollutants and metal residues.

After investigating current ASR management strategies, five end-of-life scenarios were considered, reported in Table 2, which appear strategic in the next future. More information and details about these treatments are reported in paragraph 2.2.

The first three scenarios are currently operating in Italy; however, landfill disposal after removing metals step (scenario 2) is the most adopted across Europe (Eurostat 2009).

Scenarios 4 and 5 were considered as case studies for post-shredder technology (PST) management strategies via processes which recover both material and energy. Anyway, neither of them is currently working in Italy, so it was necessary to gather data from scientific literature. Such

Table 1 Average ASR composition reported and used in this study

Material type	Average ASR composition range (wt%)	ASR composition assumed for this study (wt%)
Plastics	35–55	48
Rubber	10–20	14
Metals	6–13	11
Textiles	7–15	13
Fines (paint, glass, sand, etc.)	10–20	14

Nourreddine 2007; Boughton and Horvath 2006; De Filippi et al. 2003; Morselli et al. 2010; Laraia et al. 2007

Table 2 ASR management strategies considered for this study

End-of-life scenarios	ASR treatment management
Landfilling	ASR outcoming from an average Italian shredding plant is disposed of in landfill
Further metals recovery	Recovery of nonferrous metals from ASR in addition to the ferromagnetic fraction and residue disposal
Thermal treatment with energy recovery	ASR flow, remaining after metal recovery by scenario 2, is burnt in co-combustion with MSW for energy recovery
Advanced material recovery and incineration	Starting from scenario 2, ASR output is treated to separate plastic matters. The remaining fraction is incinerated for energy recovery
Feedstock recycling	Starting from scenario 2, ASR output is subjected to a gasification process for the production of syngas, which is subsequently converted to methanol

reference processes were the Argonne National Laboratory Process (ANL 2004) for "advanced material recovery and incineration" scenario and the Thermoselect SA (2010) process for "feedstock recycling".

2 Methodology

2.1 Goal and scope definition

2.1.1 System boundaries

According to ISO 14040 and 14044 guidelines, a cut-off criterion was applied to all flows occurring from life cycle phases prior to the ASR output from shredding plant, consistently with the principle of excluding equivalent activities for LCA comparison. Hence, system boundaries begin with the physical and geographical boundaries of each ASR treatment plant and they do end with the landfill disposal for waste and residues, or with the benefits resulting from material and energy recovering processes.

Furthermore, all environmental burdens and flows related to each ASR treatment plant and environment were considered in this study.

2.1.2 Functional unit

The amount of 1,000 kg of ASR was adopted as the functional unit of this study, constituted by different material categories (plastics, metals and alloys, textiles and fines), as shown in Table 1. Each of these main categories was further divided into the most important single fractions; Table 3 shows the amount of each material assumed for 1 t of ASR composition, according to the studies of several authors (Boughton and Horvath 2006; Nourreddine 2007; Ferrão et al. 2006).

2.1.3 Data quality assessment

According to transparency requirements for the sources of data in LCA studies, "data quality pedigree matrix" (Lindfors et al. 1995; Weidema and Wesnaes 1996) was adopted herein in order to declare the quality of data collected. For each scenario, that matrix links an indicator score of quality that ranges from 1 (the best) to 5 (the worst) concerning some of the main sources of uncertainties that may modify the reproducibility as well as the reliability of the model created. Such sources of uncertainties are data acquisition method, independence of data

Table 3 Functional unit: type material and main fractions assumed for 1 t of ASR

Plastics	kg	Metals and alloys	kg	Fines	kg	Textiles	kg	Rubber	kg
ABS	33.6	Aluminium	70.0	Paints	56.0	Natural	65.0	EPDM	140.0
PP	86.4	Copper	4.4	Glass	42.0	Synthetic	65.0		
PE	19.2	Steel	5.9	Sand	42.0				
PUR	168.0	Iron scrap	26.5						
PVC	67.2	Lead	0.4						
PA	28.8	Brass	2.8						
Other plastics	76.8								
Total	480.0	Total	110.0	Total	140.0	Total	130.0	Total	140.0

supplier, representativeness, and then temporal, geographical and technological correlations.

The best scores were achieved for the first three scenarios as a consequence of a data collection gained directly from some Italian operating plants. On the other hand, for PSTs management strategies, modelled by scenarios 4 and 5, data and issues were inventoried referring to literature sources, leading to lower scores of quality.

The Ecoinvent Database 2.0 by Swiss Centre for Life Cycle Inventories was used as flows reference related to the processes of energy production, transport and infrastructure, in each scenario modelled. In order to ensure a high consistence degree for this study, choices and assumptions were checked and verified by comparing them with the cases in reality. Table 4 shows a comparison on fuel type composition in Italian energy production between Ecoinvent Database (2008) data used for this study and those reported from statistics in 2007 by TERNA, the biggest Italian electricity transmission grid operator.

2.2 Inventory phase

Material and energy flows, inputs and environmental emissions were inventoried for each scenario. The main details and information are reported below.

Apart from scenario 1 that models the whole ASR landfilling (which is still carried out whenever any further recovering treatment from waste is not adopted by industrial plants), all other end-of-life modelled scenarios consider the recovery of nonferrous metals fractions, made by scenario 2 and amounting to 60 kg of metals, as the starting point for ASR management.

2.2.1 Scenario 1: landfilling

Modelling waste disposal in landfill involves many critical aspects due to the difficulty to establish unambiguous relationships among waste materials and their environmental impacts. Due to the lack of information available on the fate of waste after they are disposed, for each waste type material, embodied into the functional unit, some specific inventory processes were associated with high degree of detail for leachate outputs and emissions, as reported into the Ecoinvent Database (2008).

In accordance with ASR composition, it was assumed that a negligible contribution derives to biogas production from this kind of waste, even if some reactions of polymeric degradations may take place (Doka and Hischer 2005; Buttol et al. 2007; Mersiowsky 2002; Hunt 1995).

Finally, transport processes were inventoried on a distance of 150 km, which is the estimated average distance from shredding plants to landfills in Italy.

2.2.2 Scenario 2: further metals recovery

The ASR end-of-life scenario 2 consists of a sequence of operating steps dedicated to nonferrous metals recovery, modelling current Italian management strategy: most shredders use to carry out a further recovery of nonferrous metals in nonferromagnetic fraction (Morselli et al. 2010; AIRA 2007).

In order to create the second scenario for LCA analysis, an inventory of input/output flows was compiled, based on the measures from Fiori Group's Italferro plant, which is one of the biggest facilities working in Italy.

Italferro plant, located in Santa Palomba (Rome), carries out the recovery of aluminium, copper, brass, steel and residual ferrous scraps by means of eddy current machineries combined with an innovative induction sorting system process. Electricity requirements amount to 9 MJ/t.

Considering the composition of the functional unit used in this study, scenario 2 allows a separation of 60 kg of those metals from 1 t of ASR. The remaining fraction, amounting to 940 kg, will be disposed in landfill according to the assumptions of scenario 1. Other needs for auxiliary processes, such as transport to landfill (150 km) and infrastructure facilities, were also included.

The following scenarios, namely, scenarios 3, 4 and 5, consider scenario 2 such as the starting point of ASR management. Thus, 60 kg of nonferrous metals are by default recovered by all of them.

2.2.3 Scenario 3: thermal treatment with energy recovery

ASR incineration treatment is the second most adopted ASR end-of-life management system in Europe after landfilling (Eurostat 2009). However, European countries carry out a thermal treatment of ASR waste only in co-combustion with MSW mainly due to the composition of

Table 4 Comparing on fuel type composition in the Italian energy production as reported from Ecoinvent Database (2008) and statistics by Terna (2007)

Fuel type	Values used in this study from Ecoinvent Database (%)	Results from statistics by Terna (%)
Natural gas	48.6	55.5
Oil	24	20
Coke	22.3	18
Renewable fuel (most: hydroelectric)	5.1	6

the former, which presents some physical and chemical parameters resulting in difficult problems (e.g., high heating value from plastic matter or significant presence of inerts) as well as many sources of pollution such as PVC or residual oils.

Usually, ASR/MSW co-combustion rates in European Countries range from 3% to 11% (Eurostat 2009). In this study, a North Italian medium-sized incineration plant (Frullo Energia Ambiente s.r.l., Bologna, Northern Italy) was chosen as a reference for data inventory phase: in this plant, a co-combustion rate of 5% ASR is performed and no changes in inputs and outputs (emissions) are observed at this rate.

As well as for scenario 2, even this one deals with the ASR input after treatments to collect 60 kg of such nonferrous metals. By incinerating the remaining amount of 940 kg, it is possible to recover 966 MJ of electrical energy and 1,263 MJ of thermal energy, partially used for internal energy supply (about 10%). Residuals and fly ash amount to 21% and 3% of whole input, respectively; they are disposed by landfilling after inertization treatments.

Waste transport in landfill (150 km) and facility data were also included into inventory.

2.2.4 Scenario 4: advanced material recovery and incineration

The last two scenarios model PSTs as advanced waste treatments for ASR.

Reference for scenario 4 was the ANL process, developed by Argonne National Laboratory. This treatment consists of two operating steps: (i) a mechanical material separation performed to gather polymeric fractions altogether from ASR, followed by (ii) an intensive separation of each collected polymeric types by means of froth flotation (ANL 2004; Gent et al. 2009; Jody and Daniels 2006; Marques and Tenòrio 2000; Nourreddine 2007; Boughton and Horvath 2006).

In this scenario, 237 kg of single polymers (PUF, PP, PVC, PE, PP and ABS) were separated from the input of 940 kg against high inputs of energy consumptions: 981 MJ/t ASR of electrical energy (900 MJ for the froth flotation separating process, 72 MJ for waste incineration and 9 MJ from scenario 2, while thermal energy needs amount to 94 MJ). Natural gas and fresh water consumptions account for 700 MJ/t ASR and 400 kg/t ASR, respectively. Recoveries of 723 MJ of electrical energy and 945 MJ of thermal energy are then achieved by scenario 4.

Furthermore, polyurethane foams separated by ANL process are treated using a specific washing process in order to prepare this material for market. Consumptions include inputs of washing agents (1%), grid electricity (1 MJ/kg PUF) and natural gas (3 MJ/kg PUF).

Since scenario 4 models a PST which at the moment does not exist in Italy, an in situ construction was assumed: i.e. this recovery facility was set on a distance of 5 km from the Italferro shredding plant in order to minimize environmental impacts relating to transport processes.

2.2.5 Scenario 5: feedstock recycling

Even in this case, ASR treatment was modelled after the recovery obtained by scenario 2; it consists of a feedstock recycling, namely (i) a gasification process for syngas production, followed by (ii) syngas conversion to methanol and other short-chain alcohols.

An inventory of flows was carried out by referring to the Thermoselect Process SA that currently operates in Germany. This waste treatment claims inputs of ASR/MSW in the ratio 45:55. According to Drost et al. 2004; Hau et al 2008; Kaiser and Shimizu 2004; Ray and Thorpe 2007; Zhang et al. 2001, material inputs for oxygen (515 kg), zinc (3 kg), NaCl (10 kg) sulphur (2 kg) and cooling water (350 kg) were included into inventory. Scenario 5 produces 890 kg of syngas in addition to 2,566 MJ of electrical energy recovery, 27 kg of hydrogen gas and 30 kg of metals, to be added to the 60 kg separated by scenario 2. The recovered 370 kg of CO from syngas and hydrogen gas were then converted to 148 kg of methanol and chemicals. Electricity consumptions amount to 422 MJ, with 9 MJ resulting from scenario 2.

According to a sustainable development, even for this scenario the place of a gasification plant was assumed to be chosen near the shredding plant, modelling the landfill disposal of residuals and fly ash (230 kg) on a distance of 5 km (Table 5).

2.2.6 Limits and assumptions of the study

Any information or data describing possible sources of pollutants, such as fuels and oils that usually remain in ASR absorbed by textiles and foams, were not embodied into the functional unit definition. This aspect may be seen as a limit in a study that aims at evaluating environmental impacts, but it can be justified by assuming that all polluting substances were ideally removed during preshredding phase operations such as claimed by European Directives. Moreover, results from recent studies (Morselli et al. 2010) show that ASR chemical–physical parameter remains under hazardousness threshold.

Similar assumptions were found into many LCA studies dealing with end-of-life scenarios (Boughton and Horvath 2006; Choi et al. 2006; Sawyer-Beaulieu and Tam 2005, 2008; Schmidt et al. 2004).

Table 5 Main inputs and outputs considered for each scenario

End-of-life scenarios	Life cycle inventories included			
	Material recovery	Energy recovery	Processing related emissions	Landfilling with transportation
Landfilling				1,000 kg of ASR, 150 km by truck
Further metals recovery	60 kg of metals		9 MJ grid electricity	940 kg of ASR, 150 km by truck
Thermal treatment with energy recovery	60 kg of metals	966 MJ grid electricity, 1,263 MJ thermal energy	97 MJ grid electricity, 126.3 MJ thermal energy	226 kg of inertized residuals, 150 km by truck
Advanced material recovery and incineration	60 kg of metals, 237 kg of plastics	723 MJ grid electricity, 945 MJ thermal energy	981 MJ grid electricity, 94 MJ thermal energy, 700 MJ natural gas, 400 kg water; 1 MJ/kg $_{PUF}$ grid electricity, 3 MJ/kg $_{PUF}$ natural gas	169 kg of inertized residuals, 5 km by truck
Feedstock recycling	90 kg of metals, 148 kg of chemicals (methanol), 27 kg of hydrogen gas	2,566 MJ grid electricity	422 MJ grid electricity, 515 kg oxygen, 350 kg cooling water	230 kg of inertized residuals, 5 km by truck

3 Results

Impacts resulting from environmental loads of each scenario were quantified. According to ISO 14040 and 14044, ecoindicator’99 method by PRé Consultant B.V. (2001) has been adopted to characterise and quantify the main impacts in terms of potential effects on the following nine environmental categories: global warming, carcinogens, respiratory diseases from organic and inorganic substances, acidification and eutrophication effects, ecotoxicity, land use, mineral and fossil fuels depletions.

According to this method, results were then worked out by adding them into three damage end points at a higher grade of understanding that refer to Human Health, Ecosystem Quality and Resources Depletion. Units of measurement used in this study were disability adjusted life years for Human Health end point, potentially disappeared fraction of plant species (PDF*m^2*yr) and MJ surplus energy referred to ecosystem quality and resources depletion, respectively.

Table 6 and Fig. 1 show the results from impact assessment phase.

4 Discussion

4.1 Human health

According to the results, scenario 1 shows the highest environmental impact due to the effects of categories referring to the end points of human health and resources depletion. Furthermore, ASR landfilling is the only scenario modelled that does not show avoided impacts as a result of the absence of recovery steps. For that scenario, main impacts seem to be attributed to the disposal of plastics, related to *carcinogens*. In this category, the decrease of environmental impacts showed by scenarios 3, 4 and 5 is remarkable: the thermal processes of combustion and gasification may lead to a quantitative incineration of plastics, due to the combustible nature of polymers that is later followed by inertization treatments on residues before safe landfill disposal.

Considering the whole amount of polymers embodied into ASR waste (up to 45%), it can be deduced that separating plastic fractions from ASR will ensure some significant decreases in environmental impacts.

Even the categories of *respiratory organics* and *respiratory inorganics* contribute to damage Human Health, with similar impact trends. In both cases, the effects on environment seem to relate with metal fraction recovery from ASR: the best results are achieved by those scenarios that carry out a recovery of nonferrous metals output. *Climate change* completes the list of categories which show impacts on human health. For this category, it may be surprising that the worst scenario is still landfilling. Considering the material composition of ASR, it would be expected that incineration would lead to highest impacts because of the emission released during the thermal oxidation of plastics. Indeed, that waste embodies a very low organic fraction, which however could result in biogas formation, while the combustion of polymeric matters by means of thermal treatments can be considered quite complete. The reason why scenario 3 shows a lower net impact than landfill may be ascribed to the benefits

Table 6 Impact assessment results for each category considered

Impact categories	Unit	End-of-life scenarios				
		Landfilling	Further metals recovery	Thermal treatment with energy recovery	Advanced material recovery and incineration	Feedstock recycling
Carcinogens	DALY	3.26E−03	3.03E−03	2.42E−05	−6.51E−05	−2.75E−04
Respiratory organics	DALY	1.11E−07	−4.63E−08	−1.14E−07	−1.22E−06	−1.19E−06
Respiratory inorganics	DALY	4.94E−05	−3.72E−04	−3.80E−04	−8.34E−04	−7.45E−04
Climate change	DALY	1.94E−05	−5.44E−05	1.98E−06	−1.17E−04	−1.66E−05
Human health total damage	DALY	3.33E−03	2.61E−03	−3.54E−04	−1.02E−03	−1.04E−03
Ecotoxicity	PDF*m^{2}yr	6.41E+01	−6.55E+00	1.13E+02	6.38E+01	−1.12E+02
Acidification/ Eutrophication	PDF*m^{2}yr	2.08E+00	−4.33E+00	−2.22E+00	−1.16E+01	−1.39E+01
Land use	PDF*m^{2}yr	2.16E+00	−5.70E+00	−8.37E+00	−7.76E+00	−1.32E+01
Ecosystem quality total damage	PDF*m^{2}yr	6.83E+01	−1.66E+01	1.02E+02	4.44E+01	−1.39E+02
Minerals	MJ surplus	9.59E−01	−2.00E+02	−2.00E+02	−2.05E+02	−3.17E+02
Fossil fuels	MJ surplus	9.95E+01	−2.08E+02	−6.49E+02	−2.08E+03	−1.63E+03
Resources depletion total damage	MJ surplus	1.00E+02	−4.08E+02	−8.48E+02	−2.29E+03	−1.95E+03

DALY disability adjusted life year, *PDF*m^2 yr* potentially disappeared fraction of plant species

resulting from metals recovery, i.e. avoided emissions relevant to mining operations, which counterbalance the direct impacts on the environment due to incinerator emission.

4.2 Ecosystem quality

This damage end point relates to the environmental effects through the categories of *ecotoxicity*, *acidification/eutrophication* and *land use*.

Ecotoxicity is the only category in which scenario 1 does not achieve the highest impacts on environment: thermal treatment with energy recovery gets the worst score mainly due to the emissions occurring from combusting processes. In this sense, it is consistent that, even for "feedstock recycling", results show unusual higher impacts, as a consequence of gaseous outputs from gasification plant.

Similar results, but with different magnitude, are shown for the categories of *land use* and *acidification/eutrophication*. In both cases no benefit is gained by scenario 1, resulting from the disposal of the whole ASR in landfill. The only exception is showed by scenario 4: for *acidification/eutrophication*, better results are achieved in terms of avoided impacts than before, proving that it is the best scenario after feedstock recycling, concerning this end point.

4.3 Resources depletion

Fossil fuels is the impact category mainly responsible for higher effects on resource depletion.

Improvements related to the avoided impacts resulting from energy recovery processes may occur from incineration and gasification plants. As shown by Table 4, Italian energy production is based at least for 90% on fossil fuels. Thus, scenarios performing energy recovery show better result.

In addition, further benefits in terms of fossil fuels savings are achieved using separating processes that deal with the ASR plastic fraction in order to prepare it for next recycling steps. Separating polymeric matters from ASR waste will lead to higher environmental improvements since plastic recovery brings to a decrease of the demand in

Table 7 Uncertainties distribution adopted for this study, based on Weidema and Wesnaes (1996)

Monte Carlo analysis		
Type of uncertainty	Value	Process considered
Certain data	1	All material flows from directly data sources
Less certain data	1.5	Energy and thermal inputs and outputs; all emissions and avoided impacts
Uncertain data	2	Transport and infrastructure processes; all flows calculated by approximation

Table 8 Recycling and recovery rates calculated for each scenario

End-of-life scenario	% Rate	
	Recyclability	Recoverability
Landfilling	81.0	81.0
Further metals recovery	82.2	82.2
Thermal treatment with energy recovery	82.2	96.5
Advanced material recovery and incineration	86.9	97.6
Feedstock recycling	85.8	96.4
ELV directive targets in 2015	85.0	95.0

Reference: DS/EN ISO 22628

corresponding virgin materials, which are commonly obtained from oil-refining treatments.

The best result showed by “advanced material recovery with incineration” scenario may be explained according to this interpretation.

Furthermore, fossil fuels depletion strictly relates even to all the indirect activities from an industrial system, such as transport processes, manufacturing and maintenance operations or mineral processes and treatments.

Mining processes and metals manufacturing need high inputs of energy. Thus, metals recovery, especially copper and aluminium, may lead to significant environmental improvements in terms of net energy savings as it have been reported by US Department of Energy in 2006 for material type (Jody and Daniels 2006).

In the same way, even the impact category *minerals depletion* shows better results for scenarios performing the recovery of metal fractions. To confirm this, it is significant that results achieved by scenario 2 are the same of those obtained by scenario 4. In both scenarios, equal amounts of nonferrous metals are separated from ASR, while Scenario 5 shows the best result due to the added recovery of further 30 kg of metals.

5 Sensitivity analysis

From the scores shown in Fig. 1, a net preference could be given to scenarios 4 and 5 (“advanced material recovery and incineration” and “feedstock recycling”). Anyway, both

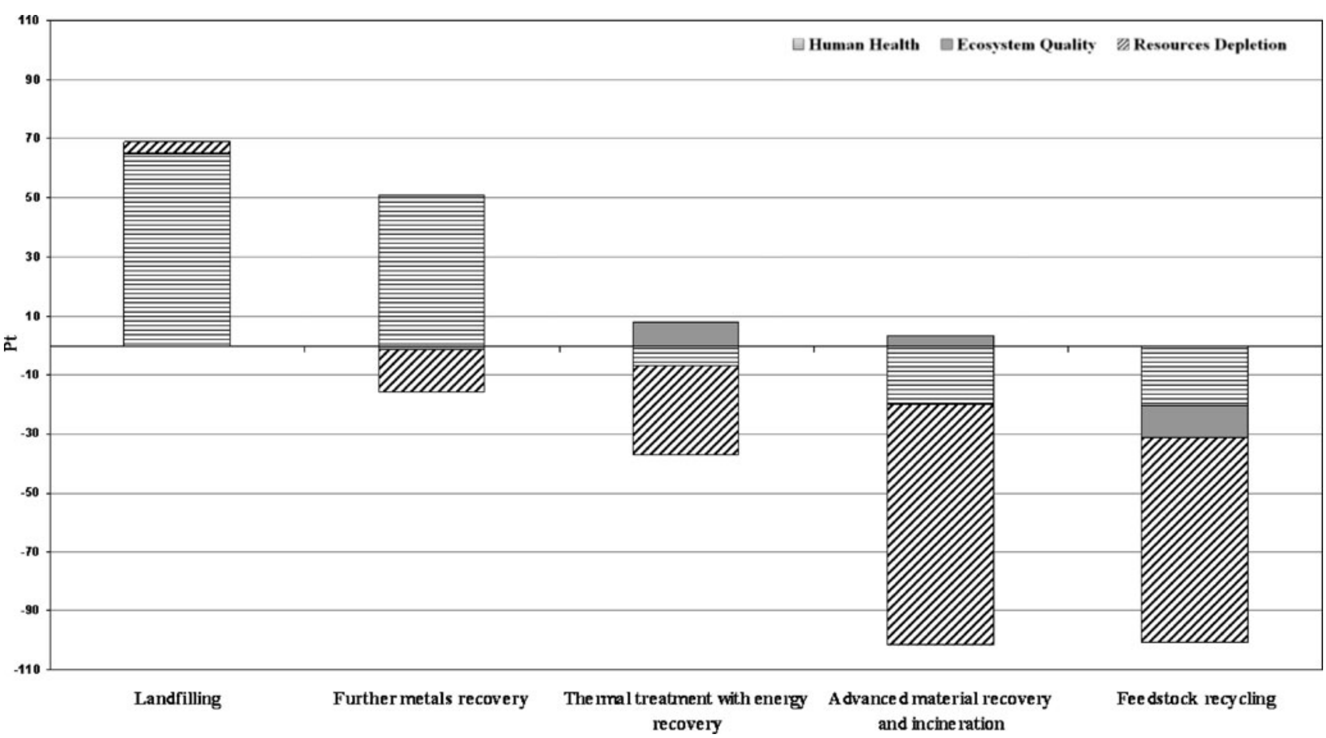

Fig. 1 Bar chart showing total damage scores for each end point according to the Eco-indicator’99 method

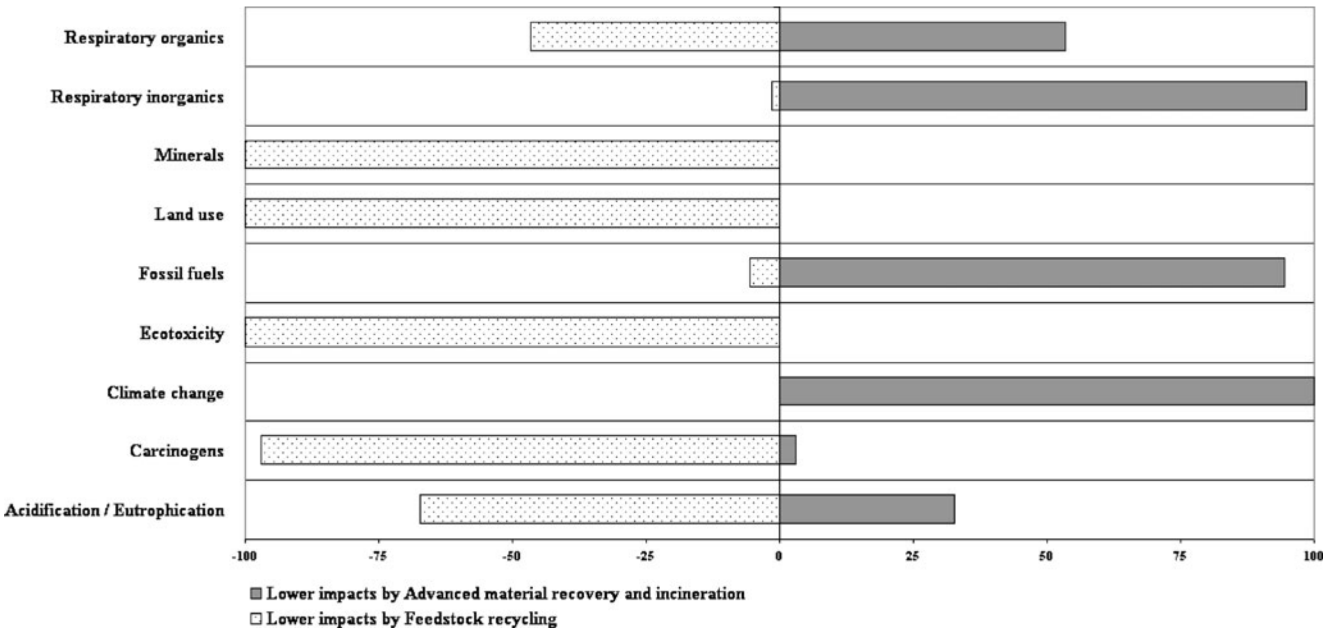

Fig. 2 Sensitivity analysis results for scenarios 4 and 5 using Monte Carlo runs

scenarios are characterised by lower data quality and reliability due to the absence of industrial plants operating in Italy, as previously mentioned.

Thus, Monte Carlo Analysis was adopted in order to evaluate on a statistical basis the results from scenarios 4 and 5. Uncertainties on input/output data were assigned using a range based on the study by Weidema and Wesnaes (1996), reported in Table 7. The lognormal statistical distribution with a confidence interval of 95% was used, while a fixed number of runs was put to 1000.

Figure 2 shows results obtained using Monte Carlo analysis: percentage rates, which are achieved by scenarios at the end of all runs, are on *x*-axis, whereas on y-axis the 11 categories adopted for the impact assessment are reported. Bars on the right represent the number of times scenario 5 had a lower environmental load than scenario 4.

In general, it can be assumed that if 90–95% of the Monte Carlo runs are favourable for a scenario, the difference may be considered significant (Pré 2001). For instance, results show that in 100% of the cases the minerals impact score is lower for scenario 5, probably due to the added 30 kg of metals further recovered, compared to scenario 4. For some other impact categories, bars show a less net preference or, even, an opposite result.

However, Monte Carlo analysis shows for both scenarios consistent results, according to the score achieved in categories considered into the impact assessment phase, supporting the good reliability and robustness of the model created.

6 Recycling and recovery rates

Table 8 shows recycling and recovery rates resulting for each scenario according to the ISO 22628 calculating procedures.

For a better understanding, 81% recycling rate was assumed such as the starting point to calculate recovery percentages for each end-of-life scenario. That rate refers to the Italian average issue resulting from those material recovery steps that commonly take place during drainage, dismantling and shredding phases (Eurostat 2009).

As shown in Table 8, it is possible to notice that scenarios 1, 2 and 3 do not allow Member States to reach ELV Directive targets in 2015. This is in line with the report GHK/BioIS (2006) by the European Commission.

On the other hand, PSTs ensure target achievement even though cost efficiency of these innovative technologies is still an open issue, since the number of industrial-scale operating plants in Europe (and around the world) is still limited. Anyway, ASR treatment appears unavoidable in order to reach those targets.

7 Conclusions

Life Cycle Assessment was applied in this study as a scientific approach aimed to characterise and quantify environmental damages and impacts resulting from different ASR management methods.

The results show that industrial processes aimed at matter recovery are not only a necessary solution to fit European recycling and recovery targets for ELVs, but also the options that can obtain greater environmental benefits compared to present practises. Furthermore:

(i) ASR landfilling is the worst scenario due to the direct impacts resulting from the disposal of polluted and hazardous waste as such ASR commonly appears, without any treatment aimed at energy or material recovery; thus, it results in a net loss of material. However, the nonferrous metals fraction recovery carried out commonly by most shredders at present allows a reduction of environmental loads, even if strictly for resources consumption.

(ii) ASR co-combustion in incinerator would allow a decrease in damages related to plastics landfilling, and further benefits related to energy recovery processes, like waste volume reduction and organic pollutants destruction. In spite of the advantage resulting from the opportunity to operate in co-combustion with MSW (at the rate of 5%, any significant variations in outputs were not observed), ASR incineration should not be considered as a long-term alternative to landfill since this end-of-life strategy do not allow the achievement of 85% recycling target fixed by the European Community.

(iii) In terms of environmental impact, better results characterise post-shredder technologies modelled by scenarios 4 and 5, with a little advantage for “feedstock recycling”. It is interesting to compare results even on the recycling and recovery rates gained by those scenarios: both allow the attainment of European targets, but scenario 4 reaches a higher recycling score than the other, competing with the other strategy in being considered the best solution. Hence, identifying the best way to treat ASR waste may be quite difficult even as a consequence of the frequent variations that occur in ASR composition.

Of course, in this study it was not possible to consider the whole range of technologies available at the present time, and the existence of other processes leading to further environmental improvement is not excluded. However, despite uncertainties and assumptions that commonly affect LCA studies, a comparison was performed among the most common management methods focusing on recycling and recovery rates, together with an assessment of environmental effects.

Finally, further improvements will be achieved only by integrating end-of-life treatments into eco-design strategies aiming at a more efficient separation of high value-added materials such as plastics and metals, and leading to a reduction of waste outputs from ELVs management chain.

References

ACEA (2009) European Motor Vehicle Parc 2007. In: http://www.acea.be/index.php/collection/statistics. Accessed May 2010

AIRA (2007) Report 2007. In: http://www.airaassociazione.it Accessed May 2010

ANL (2004) http://www.anl.gov.html, http://www.transportation.anl.gov/materials/crada_recycling.html. Accessed May 2010

Boughton B, Horvath A (2006) Environmental assessment of shredder residue management. Resour Conservat Recycl 47:1–25

Buttol P, Masoni P, Bonoli A, Goldoni S, Belladonna V, Cavazzuti C (2007) LCA of integrated MSW management system: case study of the Bologna District. Waste Manage 27:1059–1070

Choi BC, Shin HS, Lee SY, Hur T (2006) Life cycle assessment of a personal computer and its effective recycling rate. Int J Life Cycle Assess 11(2):122–128

Dalmijn WL, De Jong TPR (2007) The development of vehicle recycling in Europe: sorting, shredding, and separation. JOM-US 59:52–56

De Filippi P, Pochetti F, Borgianni C, Paolucci M (2003) Automobile shredder residue gasification. Waste Manag Res 21:459–466

DIRECTIVE 2000/53/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 Sept 2000 on end-of-life vehicles

Doka G, Hischer R (2005) Waste treatment and assessment of long term emissions. Int J Life Cycle Assess 10(1):77–84

Drost U, Eisenlihr F, Kaiser B, Kaiser W, Stahlberg R (2004) Report on the operating trial with automotive shredder residue (ASR). In: 4th International Automobile Recycling Congress, Geneva, Switzerland 1–20

DS/EN ISO 22628 Road vehicles—Recyclability and Recoverability—Calculation method, 2002-02-15

Ecoinvent Database (2008) http://www.ecoinvent.ch. Accessed May 2010

Eurostat (2009) http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/elvs. Accessed May 2010

Ferrão P, Amaral J (2006) Assessing the economics of auto recycling activities in relation to European Union Directive on end of life vehicles. Technol Forecast Soc Change 73:277–289

Ferrão P, Nazareth P, Amaral J (2006) Strategies for meeting EU end-of-life vehicles reuse/recovery targets. J Ind Ecol 10(4):77–93

Funazaki A, Taneda K, Tahara K, Tanaba A (2003) Automobile life cycle assessment issues at end-of-life and recycling. JSAE Rev 24:381–386

Gent MR, Menendez M, Torano J, Isidro D (2009) Recycling of plastic waste by density separation: prospect for optimization. Waste Manage Res 27:175–187

GHK/Bios (2006) A study to examine the benefits of the End of Life Vehicles Directive and the cost and benefits of a revision of the 2015 targets for recycling, re-use and recovery under the ELV Directive. Final Report to DG Environment, Birmingham, J2232

Hau JL, Ray R, Thorpe RB, Azapagic A (2008) A thermodynamic model of the outputs of gasification of solid waste. Int J Chem React Eng 6, Article A35

Hunt RG (1995) LCA consideration of solid waste management alternatives for paper and plastics. Resour Conservat Recycl 14:225–231

Jody BJ, Daniels EJ (2006) End-of-life vehicle recycling: the state of the art of resource recovery from Shredder residue,. In: Argonne National Laboratory, Energy Systems Division, U.S. Department of Energy, Chicago. In: <www.osti.gov/bridge>, www.anl.gov. Accessed May 2010

Kaiser W, Shimizu M (2004) High-temperature gasification—The Thermoselect process. Waste Manage World, Nov-Dic, Thermal Treatment 79–86

La Mantia F (2002) Handbook of plastic recycling, Shawbury (UK), Rapra Technology Limited

Laraia R, Foschini F, Frittelloni V, APAT (2007) La gestione dei veicoli fuori uso: stato attuale e prospettive. In: Morselli L (ed) Atti di Ecomondo, vol 2. Maggioli Editore, Dogana (RSM), pp 591–599

Lindfors LG, Christiansen K, Hoffman L, Virtanen Y, Juntilla V, Hansenn OJ et al (1995) On the nordic guidelines on life cycle assessment. Int J Life Cycle Assess 1(1):45–48

Marques GA, Tenòrio JAS (2000) Use of froth flotation to separate PVC/PET mixtures. Waste Manage 20:265–269

Mersiowsky I (2002) Long term fate of PVC products and their additives in landfills. Prog Polym Sci 27:2227–2277

Morselli L, Santini A, Passarini F, Vassura I (2010) Automotive shredder residue (ASR) characterization for a valuable management. Waste Manage, in press. doi:10.1016/j.wasman.2010.05.017

Nourreddine M (2007) Recycling of auto shredder residue. J Hazard Mater 139:481–490

Pré Consultant (2001) The eco-indicator '99—a damage oriented method for life cycle impact assessment, methodology report, Third edition, Product Ecology Consultants. In: http://www.pre.nl/eco-indicator99/ei99-reports.htm. Accessed May 2010

Ray R, Thorpe RB (2007) A comparison of gasification with pyrolisis for the recycling of plastic containing wastes. Int J Chem React Eng Volume 5, Article A85

Reuter MA, van Schaik A, Ignatenko O, de Haan GJ (2006) Fundamental limits for the recycling of end-of-life vehicles. Min Eng 19:433–449

Sawyer-Beaulieu SS, Tam EKL (2005) Applying Life Cyce Assessment (LCA) to North American End-of-Life Vehicle (ELV) management processes. SAE Technical Paper Series, SAE International 2005-01-0846

Sawyer-Beaulieu SS, Tam EKL (2008) Constructing gate to gate Lie Cycle Inventory (LCI) of End-of-Life Vehicle (ELV) dismantling and shredding processes. SAE Technical Paper Series, SAE International 2008-01-183

Scheirs J (2001) Polymer recycling, Australia. Science, Technology and Application

Schmidt WP, Dahlqvist E, Finkbeiner M, Krinke S, Lazzari S, Oschmann D, Pichon S, Thiel C (2004) Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. Int J Life Cycle Assess 9(6):405–416

TERNA (2007) Dati statistici sull'energia elettrica in Italia nel 2007. In: http://www.terna.it. Accessed May 2010

Thermoselect SA (2010) http://www.thermoselect.com. Accessed May 2010

Weidema BP, Wesnaes M (1996) Data quality management for life cycle inventories—an example for using data quality indicators. J Clean Prod 4(3–4):167–174

Zhang Y, Sun Y, Zhong B (2001) Synthesis of higher alcohols from Syngas over ultrafine Mo-Co-K Catalysts. Catal Lett 76(3–4)/October